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# STUDY OF A FAMILY OF DIFFUSERS FOR LOW REYNOLDS NUMBER HYPERSONIC WIND TUNNELS

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## NOTATIONS

| | |
|---|---|
| $A$ | area of a jet section |
| $Cx$ | drag factor |
| $d$ | dynalpy: $d = p + pu^2$ |
| $D$ | dynalpy reduction factor |
| $F$ | resultant of the forces of friction on the diffuser |
| $H$ | form parameter of the boundary layer: $H = \frac{\delta_1}{\delta_2}$ |
| $L$ | length |
| $M$ | Mach number |
| $\overline{M}$ | Mach number of the mean flow, equivalent to the flow leaving the nozzle |
| $p$ | static pressure |
| $\overline{p}_r$ | mean pressure on the inner surface of the intake entrance |
| $Q$ | delivery reduction factor |
| $r$ | distance from a point of the boundary layer to the axis of the nozzle |
| $R$ | radius of a jet section |
| $T$ | drag of the ensemble formed by a model and its support |
| $u$ | velocity at a point of the flow |
| $X$ | distance from the nozzle outflow plane to the intake entrance plane |
| $y$ | distance from a point of the boundary layer to the wall |
| $\alpha$ | angle |
| $\gamma$ | specific heat ratio |
| $\Gamma$ | recompression produced by the diffuser: $\Gamma = P_{e\,max}/P_0$ |
| $\delta$ | thickness of the boundary layer |
| $\delta_1$ | displacement thickness |
| $\delta_2$ | motion quantity thickness |
| $\overline{\delta_1}$ | $= \int_0^\delta \left(1 - \frac{\rho U}{\rho_\delta U_\delta}\right) \frac{r}{R}\, dy = \delta_1 - \delta_1^2/2R$ |
| $\overline{\delta_2}$ | $= \int_0^\delta \left(1 - \frac{U}{U_\delta}\right) \frac{\rho U}{\rho_\delta U_\delta} \frac{r}{R}\, dy = \overline{\delta_1}/\overline{H} = \delta_2 - \delta_2^2/2R$ |
| $\phi$ | diameter of a jet section |
| $\Phi M$ | $= (1 + \gamma M^2)\, \varpi(M)\, \Sigma(M)$ |
| $\varpi(M)$ | isentropic expansion ratio: $\overline{\omega}(M) = p/p_r$ |
| $\pi(M)$ | ratio of the generating pressures on either side of a normal shock to the Mach number: $\pi(M) = p_r'/p_r$ |
| $\rho$ | volumetric mass |
| $\Sigma(M)$ | law of areas for an isentropic flow: $(M) = A/A^*$ |

The subscripts have the following signicance:

| | |
|---|---|
| c | the conditions in the box |
| d | the diverging element (baffle) |
| e | the extraction conditions |
| i | the generating conditions |
| m | the mixer |
| r | the intake |
| s | the conditions in the output plane of the mixer |
| S + M | the support-model ensemble |
| $\delta$ | the conditions at the border of the boundary layer |
| 0 | the conditions in the output plane of the nozzle |
| * | the neck of the nozzle. |

# STUDY OF A FAMILY OF DIFFUSERS FOR LOW REYNOLDS NUMBER HYPERSONIC WIND TUNNELS

B. Monnerie

ABSTRACT. After having demonstrated the advantage of using a diffuser in a low density hypersonic wind-tunnel, a method is proposed for evaluating the overall performance of a family of diffusers consisting of a conical intake followed by a cylindrical mixing section. Results obtained with this system are compared with experimental data, illustrating the effect of various geometrical parameters of the diffuser on the recovery of achievable pressure.

## I. INTRODUCTION

Until quite recently, in the preliminary planning of rarefied gas wind-tunnels, no attention was paid to the advantages that might be derived from a natural recompression of the flow in a diffuser. The most frequent reason for this lack of interest was the fact that the Mach number and the static jet pressure were low, so that the recompression that could be achieved in a diffuser was negligible. /9*

As we shall see, the situation changes for a high Mach number. Here, it is possible to achieve high enough recompression rates to make it possible to do without one or more of the pumping stages which ensure the operation of the tunnel. /10

The results presented below concern the study of a particular family of diffusers of very simple conception. The first part of the discussion deals with an evaluation of the performance that may be expected of diffusers of this kind. In the second part of the discussion, these results are compared wit experimental data.

## II. PERFORMANCE EVALUATION

### II. 1. Description of the Type of Diffuser Selected

This diffuser is designed for use in an open jet wind-tunnel, equipped with a hypersonic nozzle. The diffuser itself is a body of revolution, comprised of:

1. a truncated conical intake of $\phi_r$ entrance diameter and $\alpha_r$ angle;
2. a cylindrical mixer of $\phi_m$ diameter and of $L_m$ length; and
3. a baffle designed to ensure communication with the pumping channel.

A diffuser of this configuration has already been successfully used at AEDC [1] and [2]. The nozzle-diffuser system is housed in a chamber in which the pressure $p_c$ is established.

*Numbers in the margin indicate pagination in the foreign text.

## II.2. Evaluation of Maximum Recompression

Diffuser performance is evaluated with the help of the theorem of the quantity of motion, applied to the flow portion contained between the nozzle output and the mixer output, in a manner similar to that developed in [3], assuming the following simplified hypotheses:

1. the nozzle is assumed to be correctly primed: $p_c < p_0$, where $p_0$ is the output pressure of the nozzle;
2. the flow is uniform outside the boundary layers (Mach number $M_0$, pressure $p_0$) in the output section of the nozzle;
3. the Mach number is high: $M_0^2 >> 1$;
4. the flow in the diffuser is adiabatic;
5. the flow is subsonic and uniform in the output section of the mixer. If the flow is not uniform, it will be replaced by the equivalent subsonic flow which transports the same delivery rate, the same quantity of motion, and the same energy as the real flow (see [4] for the concept of the mean flow);
6. the external wall friction acting on the surfaces washed by the still water of the housing chamber is negligible.

Note the following:

$\bar{p}_r$ - the mean pressure prevailing on the inner surface of the intake;
F - the resultant of the forces of friction on the intake and in the mixer;
Q - the delivery reduction factor:

$$Q = \frac{\text{real delivery of nozzle}}{\rho_0 U_0 A_0} \quad ;$$

D - the dynalpy reduction factor:

$$D = \frac{\text{total dynalpy leaving the nozzle}}{(p_0 + \rho_0 U_0^2)\ A_0} \quad .$$

The equations for the conservation of delivery and dynalpy for the closed surface shown in **Figure 1** lead to:

$$\frac{Q p_0 A_0}{\varpi(M_0)\,\Sigma(M_0)} = \frac{p_s A_m}{\varpi(M_s)\,\Sigma(M_s)} \tag{1}$$

$$\frac{p_s}{p_0} = \frac{1}{(1 + \gamma M_s^2)} \left[ D(1 + \gamma M_0^2)\frac{A_0}{A_m} + \frac{p_c}{p_0}\frac{A_r - A_0}{A_m} - \frac{\bar{p}_r}{p_0}\frac{A_r - A_m}{A_m} - \frac{F}{p_0 A_m} \right]. \tag{2}$$

An evaluation of the order of magnitude of the different terms found in square brackets in Equation (2), carried out during specific experiments in which $A_m$ is in the order of $A_0$, indicates that, in the first approximation, the last three terms may be disregarded with respect to the first.

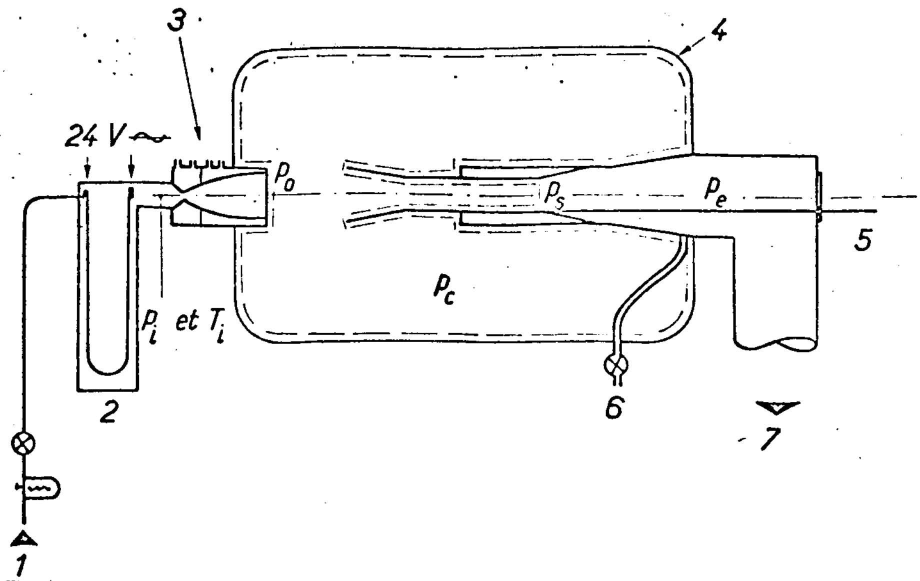


Figure 1. Installation Diagram.

1. Compressed air intake; 2. Heater; 3. Nozzle cooling; 4. Measuring chamber; 5. Diffuser displacement control; 6. Injection device; 7. Outlet to mechanical pumping group.

Equation (2) then becomes /11

$$\frac{p_s}{p_0} = D \, \frac{1 + \gamma M_0^2}{1 + \gamma M_s^2} \, \frac{A_0}{A_m}. \tag{3}$$

By comparing Equation (3) and Equation (1), $M_s$ can be calculated by

$$(1 + \gamma M_s^2) \, \varpi (M_s) \cdot \Sigma (M_s) = \Phi (M_s) = \frac{D}{Q} \, \Phi (M_0) \tag{4}$$

where D and Q are functions of the flow characteristics at the nozzle outlet ([4] and [5]):

$$Q = 1 - \frac{2 \bar{\delta}_1}{R_0} = \left[1 - \frac{\delta_1}{R_0}\right]^2$$
$$D = 1 - \frac{2 \bar{\delta}_1}{R_0} \, \frac{1 + 1/\bar{H}}{1 + 1/\gamma M_0^2}. \tag{5}$$

Since the Mach number is assumed to be high, $\bar{H}$ and $\gamma M_0^2$ are large with respect to unity; consequently:

$$\frac{1 + 1/\bar{H}}{1 + 1/\gamma M_0^2} \simeq 1 \qquad D \simeq Q$$
$$\Phi (M_s) \simeq \Phi (M_0). \tag{6}$$

Relation (6) between $M_s$ and $M_0$ is that which links the Mach numbers on either side of a right-angle shock [4]. In the hypersonic region, the Mach number downstream from the normal shock tends toward the limiting value $\sqrt{\frac{\gamma - 1}{2\gamma}}$. As a result:

$$M_s \simeq \sqrt{\frac{\gamma - 1}{2\gamma}}. \tag{7}$$

The extraction pressure $p_e$ prevailing at the end of the subsonic diffuser, which is a continuation of the mixer, is then computed on the basis of $p_s$ and $M_s$:

$$p_e = [1 + \gamma/2\ M_s^2]\ p_s \tag{8}$$

and

$$\frac{p_e}{p_0} = \frac{p_e}{p_s}\frac{p_s}{p_0} = \frac{\gamma M_0^2}{1 + \gamma/2\ M_s^2}\left[1 - \frac{\delta_1}{R_0}\right]^2 \frac{A_0}{A_m}$$

whence:

$$\boxed{\frac{p_e}{p_0} = \frac{4\gamma}{3 + \gamma} M_0^2 \left[1 - \frac{\delta_1}{R_0}\right]^2 \left[\frac{\varnothing_0}{\varnothing_m}\right]^2}. \tag{9}$$

## II.3. Validity Limitations

Thus found, Equation (9) clearly indicates the effect on diffuser performance:

- on the one hand, of the aerodynamic parameters which determine the flow state at the nozzle output (Mach number $M_0$, initial boundary layer $\delta_1/R$);
- on the other hand, of the sole geometric parameter $\phi_m$, mixer diameter.

The other geometric parameters of the diffuser ($\phi_r$, $\alpha_r$, $L_m$) do not appear to exert any influence. On the other hand, it must be borne in mind that the calculation procedure employed to establish Equation (9) is valid only insofar as the hypotheses initially postulated are verified, in particular, the following two:

a. the nozzle is properly primed: $p_c \leq p_0$;
b. the real flow at the output of the mixer approximates the mean equivalent subsonic flow. In effect, any flow which, at the end of the mixer, contained supersonic elements, would lead to $p_e/p_s$ values of much less than 1.

If the parameters $\phi_r$ and $\alpha_r$ have arbitrary values, condition "a" above will not be realized. For example, assuming that there is no intake and with $\phi_r = \phi_m < \phi_0$, it will not be possible to obtain $p_c \leq p_0$. Similarly, it will be seen that if the diffuser is too short, condition "b" cannot be verified.

It is therefore necessary, in order to justify the use of Equation (9), to utilize a diffuser whose geometric parameters $\phi_r$, $\alpha_r$, and $L_m$ have been properly defined on the basis of systematic experimentation. Moreover, contrary to what Equation (9) might appear to imply, it will not be possible to increase the recompression beyond a certain limit by reducing $\phi_m$. In fact, when $\phi_m << \phi_0$, first, the complimentary terms of Equation (2) are no longer negligible, and, second, the flow recompression conditions in the intake of the diffuser become very severe, and it is virtually impossible to find an intake profile to satisfy condition "b".

Finally, the jet priming conditions also limit the value of $\phi_m$. In the transition phase, during which recompression is effected by a normal shock, supposedly located in the vicinity of the nozzle output plane, it is necessary to have:

$$\Lambda_m > \frac{\Lambda_0}{\Sigma(\mathrm{M})\ \pi(\mathrm{M})} \tag{9b}$$

and thus

$$\Lambda_m > \frac{\Lambda_0}{1{,}29} \tag{9c}$$

## II.4. Remarks

II.4.1. The presence of a model and its supporting structure in the jet may be taken into consideration in the calculation procedure outlined above. Let T be the drag of the model-support total system

$$\mathrm{T} = \gamma/2\, p_0 \mathrm{M}_0^2\, [\mathrm{SC}_x]_{\mathrm{S+M}}. \tag{9d}$$

The complimentary term $T/p_0A_m$, corresponding to the losses caused by the model, is introduced in the parentheses of the second member of Equation (2), and leads to a decrease of the recompression:

$$\frac{\Delta\Gamma}{\Gamma} = \frac{\mathrm{T}}{p_0\Lambda_m}\,\frac{\Lambda_m}{\gamma\mathrm{M}_0^2\Lambda_0\mathrm{Q}} = \frac{1}{2}\,\frac{[\mathrm{SC}_x]_{\mathrm{S+M}}}{\mathrm{Q}\Lambda_0} \tag{9e}$$

II.4.2. The evaluation of $\bar{\Gamma}$ is of interest during the wind-tunnel design stage, when the jet static pressure level is fixed. Nevertheless, a more general relation, independent of the nozzle output conditions, may also be obtained. Preservation of the delivery between the surge chamber and the mixer output, maintaining the same hypotheses as before (adiabatic and uniform flow at the output of the mixer), leads to the following relation between the generating pressure $p_i$ and the extraction pressure $p_e$:

$$p_i A^* = \frac{p_e A_m}{\Sigma(M_s)}. \tag{10}$$

Within the context of the approximations of Section II.2., Equation (10) becomes

$$p_e = p_i \frac{A^*}{A_m} \Sigma\left(\sqrt{\frac{\gamma - 1}{2\gamma}}\right) \tag{11}$$

or

$$p_e \simeq 1{,}65\, p_i \frac{A^*}{A_m} \text{ for } \gamma = 1{,}4. \tag{11a}$$

## III. EXPERIMENTAL RESULTS /12

### III.1 Test Conditions

III.1.1. The priming and operating conditions of the diffuser have been studied for a case in which the especially uniform upstream flow is furnished by a contoured nozzle having the following essential characteristics:

- diameter at the neck 8 mm;
- external diameter 134 mm;
- mean Mach number at output 7.8;
- constant generating conditions: $T_i$ = 700° K; $p_i$ = 1060 mb.

III.1.2. The diffuser, of the type described in Section II (Figure 2), slides within a channel of diameter greater than $\phi_m$. This arrangement allows a continual varying of the distance from the output plane of the nozzle to the input plane of the diffuser, and owes its conception to a similar device, whose use is mentioned in [1] and [2].

The configurations tested are listed in Table 1, in which each is given an identifying number.

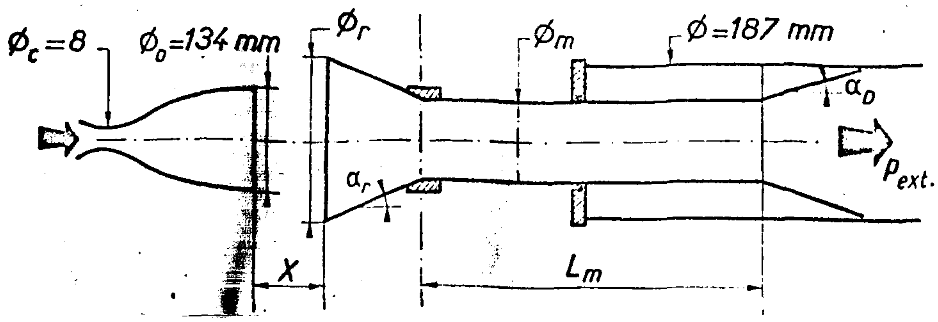


Figure 2. Definition of Geometric Parameters

TABLE 1.

| Configuration | | Intake | | Mixer | | Baffle |
|---|---|---|---|---|---|---|
| guidemarks | | $\varnothing_r$ mm | $\alpha_r$ degrees | $\varnothing_m$ mm | $L_m$ mm | $\alpha_d$ degrees |
| $C_0$ | ○ | None | | 143 | 1 500 | 3 |
| $C_1$ | ○ | 225 | 6 | 143 | 1 500 | 3 |
| $C_2$ | ⊗ | 185 | 6 | 143 | 1 500 | 3 |
| $C_3$ | ● | 270 | 6 | 143 | 1 500 | 3 |
| $C_4$ | □ | 205 | 3 | 143 | 1 500 | 3 |
| $C_5$ | △ | 225 | 12 | 143 | 1 500 | 3 |
| $C_6$ | ⊖ | 225 | 6 | 143 | 1 000 | 3 |
| $C_7$ | ⊕ | 225 | 6 | 143 | 2 000 | 3 |
| $C_8$ | ▲ | 225 | 6 | 131 | 1 500 | 3 |
| $C_9$ | ◘ | 225 | 6 | 159 | 1 500 | None |

## III.2. Test Procedure

For each diffuser configuration, the maximum extraction pressure compatible with correct priming of the nozzle ($p_c < p_o$) is the object of a systematic analysis. /13

Since the distance $|X|$ between the nozzle output plane and the input plane of the diffuser intake is fixed and the generating pressure $p_i$ is held constant, the extraction pressure $p_e$ is obtained by injecting an auxiliary flow directly upstream from the pumping group. The corresponding behavior of the box pressure $p_c$ is illustrated in Figure 3.

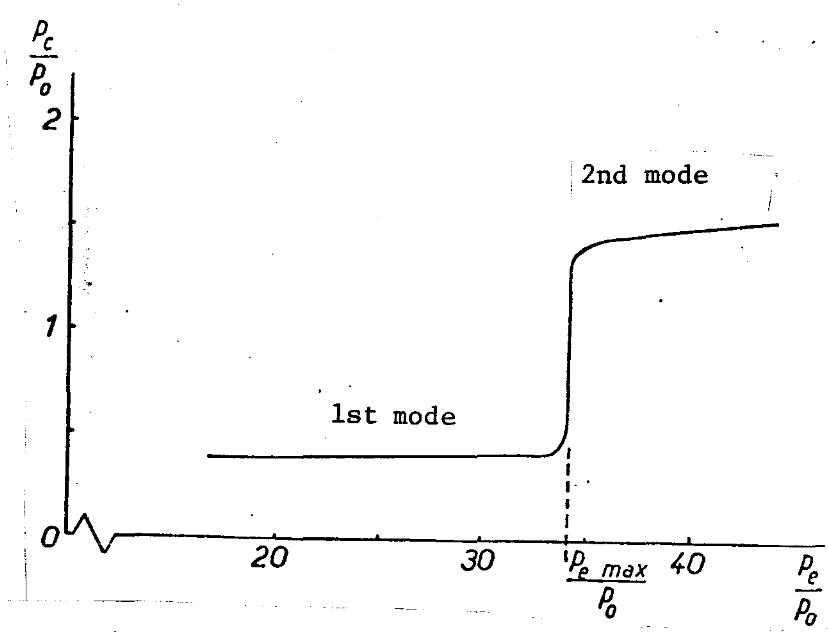


Figure 3. Evolution of the Pressure as a Function of the Extraction Pressure (Configuration 1. X = 350 mm)

This curve illustrates the two operational modes. Only the first mode, characterized by a quite constant chamber pressure, permits the fulfillment of the nozzle priming condition. The transition from the first mode to the second occurs rather abruptly, thus enabling us to define the maximum pressure of extraction without ambiguity.

The results obtained for different values of $|X|$ lead to the curve $r = F(X)$, shown in Figure 4, which indicates a maximum for a value X = X optimum. It will be observed that the values of $|X|$ opt evolve quite amply from one configuration to another: $1.5 < X/\phi_0 < 4.5$.

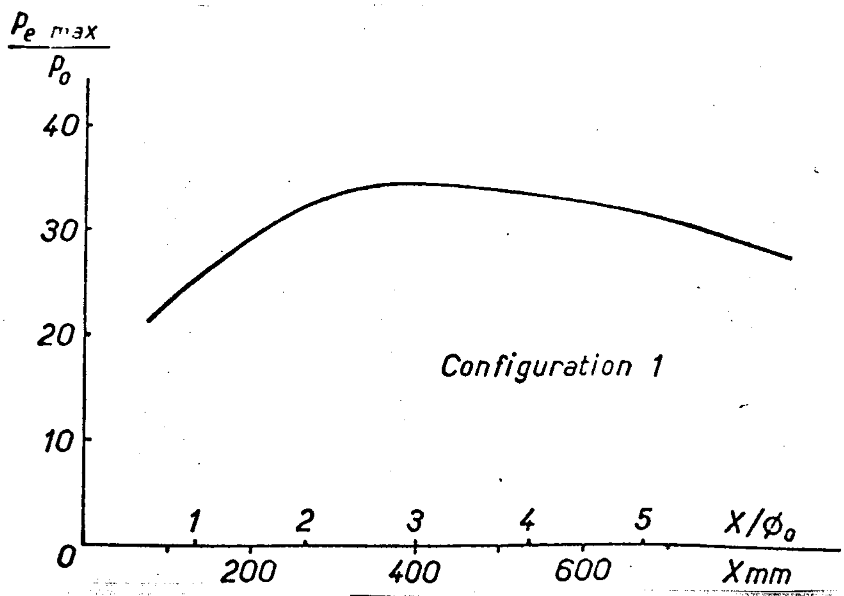


Figure 4. **Pressure Recovery in the Diffuser - Effect of the Free Jet Length X.**

### III.3. Study of the Diffuser: Effect of the Geometric Parameters /14

#### III.3.1. General

The experiments conducted have made it possible to specify, on an overall basis, the role of each of the diffuser elements, and to verify the extrapolations derived from the calculations outlined in Section II:

**- the intake element has no direct effect on the maximum recompression (Figures 5 and 6).**

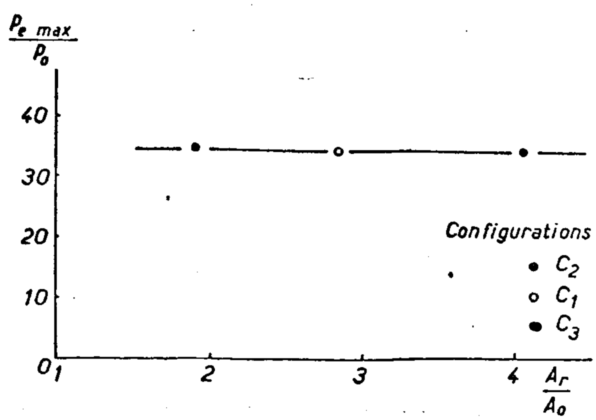


Figure 5. Pressure Recovery in the Diffuser: Effect of the Entrance Section $A_r$ ($\alpha_r = 6°$; $X = X_{opt}$)

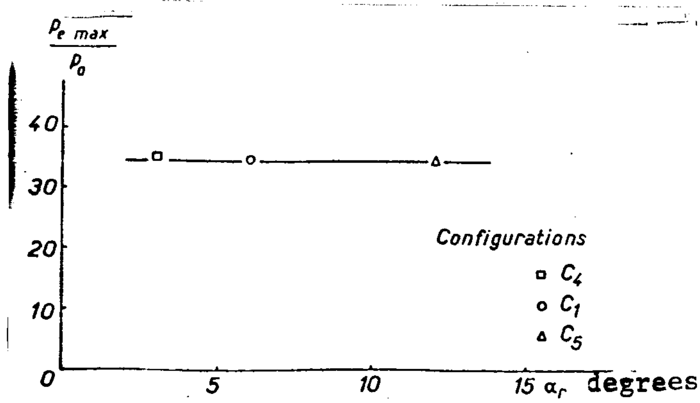


Figure 6. Pressure Recovery in the Diffuser: Effect of the Angle of Intake $\alpha_r$; ($\phi_r \sim$ const, $X = X_{opt}$)

III.3.2. Diffuser Entrance, Intake Condition

Close analysis of the adhesion conditions of the jet ejected from the nozzle on the diffuser entrance has not yet been possible. This is due to the lack of display facilities permitting a detailed study of the phenomena and flows involved, which becomes very complex in this area. Nevertheless, the first operational mode, which appears in Figure 3 and is characterized by constant box pressure, suggests the existence of a laminar flow of a supersonic type. This flow would probably develop at the entrance to, or in the immediate vicinity of, the connection with the mixer. On the other hand, the second mode lends itself to an analagous interpretation, where the operation of supersonic ejectors is a mixed mode, in which the jet discharged from the nozzle is progressively degraded and adheres to the mixer wall far downstream from the intake [3].

Under these conditions, it appears that the role of a well designed entrance consists of establishing the supersonic mode, in order to ensure a sufficiently low box pressure to permit complete priming of the nozzle.

The effect of the geometric parameters of the intake (relative entrance section and angle) on the level of the box pressure $p_c$ is shown in Figures 7 and 8. For a fixed angle of intake, there is an optimum entrance diameter leading to a minimum value of $p_c$, while in the case of an imposed entrance diameter, $p_c$ decreases at the same rate as the angle of convergence.

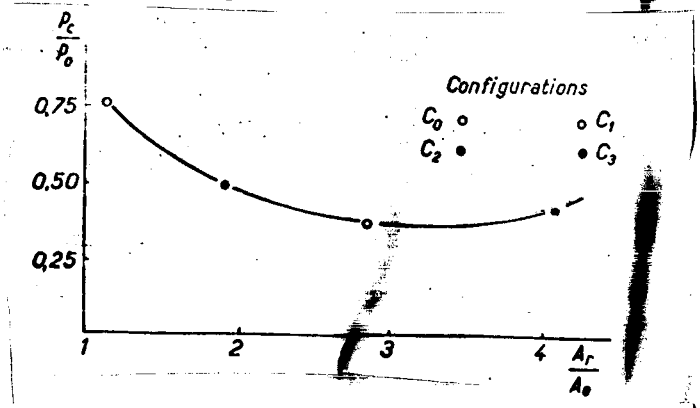


Figure 7. Pressure in the Measurement Chamber: Effect of the Entrance Section $A_r$ ($\alpha_r = 6°$, $X = X_{opt}$)

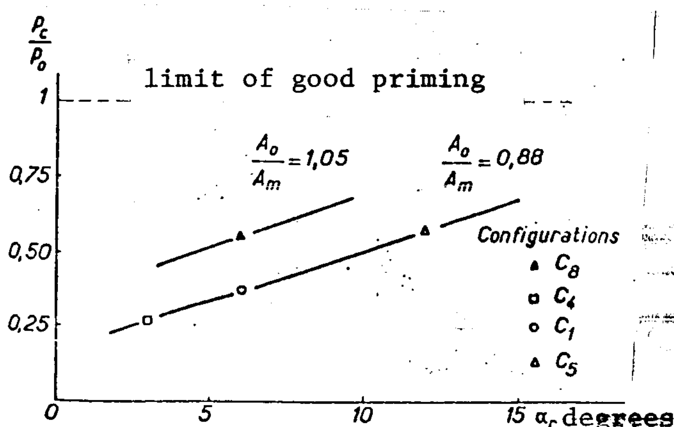


Figure 8. Pressure in the Measurement Chamber: Effect of the Intake of Angle $\alpha_r$ ($\phi_r \sim$ const., $X = X_{opt}$)

Bearing these results in mind, a satisfactory method of proportioning the intake may be obtained on the basis of the following characteristics:

$$\frac{A_r}{A_e} \sim 3 \qquad \text{(Figure 7)},$$

$$3° < \alpha_r < 6° \qquad \text{(Figures 8 and 9)}.$$

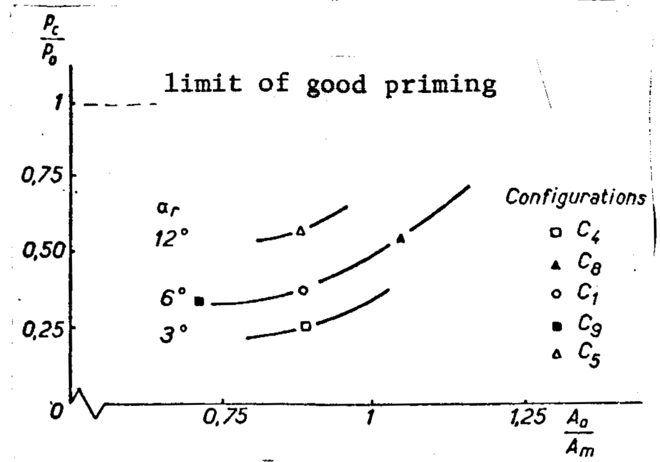


Figure 9. Pressure in the Measurement Chamber: Effect of the Mixer Section $A_m$ ($X = X_{opt}$)

The need to approximate these optimal values becomes evident when the mixer section is smaller than the nozzle output section, which leads to very significant recompression rates.

### III.3.3. Mixer

The analysis made in Section II indicates that diffuser performance essentially depends on the diameter of the mixer, provided that the length $L_m$ is sufficient for the establishment of a subsonic condition at its extremity. Otherwise, the recoverable pressure above the pumps is noticeably lower.

This fact is confirmed by the results shown in Figure 10: when $L_m/\phi_m$ increases, the recovery obtained rises to a maximum value, which probably corresponds to the establishment of the subsonic mode at the end of the diffuser. An additional increase of $L_m/\phi_m$ entails a reduction of the recovery rate, as a result of losses due to friction against the wall. For a nearly optimum $L_m$ value, the effect of the mixer diameter is reflected by a linear relationship between $\Gamma$ and $\frac{A_0}{A_m}$ (Figure 11), as anticipated in Equation (9).

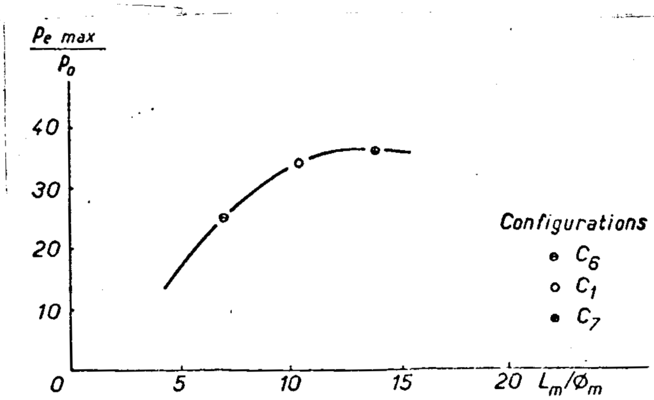


Figure 10. Pressure Recovery in the Diffuser: Effect of the Mixer Length ($X - X_{opt}$)

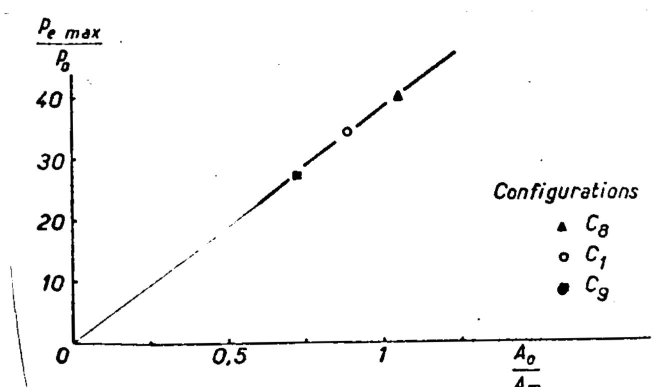


Figure 11. Pressure Recovery in the Diffuser: Effect of the Mixer Section $A_m$ ($X = X_{opt}$)

### III.3.4. Overall Performance of the Diffuser. Comparison with Calculations

The results obtained for the different configurations tested have been compared (Figure 12) with the approximate calculation based on the application of Equation (9). This comparison also makes use of the experimental results in Reference [2]. The aggregate of the results is clearly situated on a straight line of 0.8 inclination, indicating a 20% loss with respect to theoretical predictions. Bearing in mind the results of Section III.3.1. (Figures 5 and 6), this loss may be ascribed primarily to the elimination of the friction term in Equation (2). /14 /16

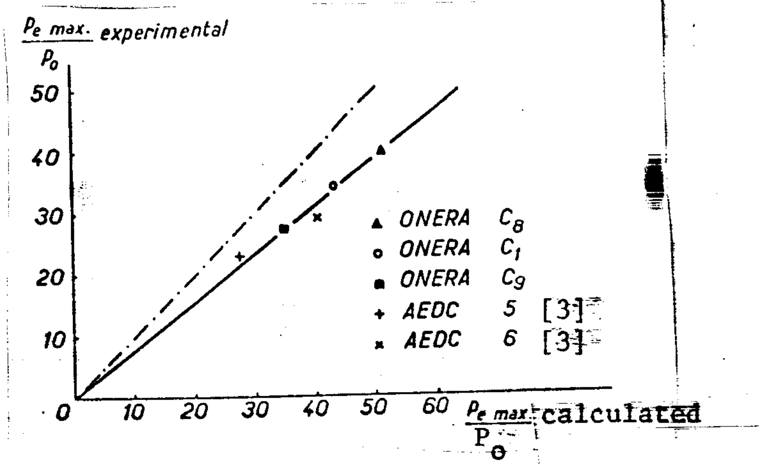


Figure 12. Pressure recovery in the Diffuser: Comparison with the Calculation

Lacking a precise estimate of the omitted term, Equation (9) may be replaced by an empirical relation of the form

$$\frac{P_{e\,max}}{P_0} = K \frac{4\gamma}{3+\gamma} M_0^2 \left[1 - \frac{\delta_1}{R_0}\right]^2 \left[\frac{\varnothing_0}{\varnothing_m}\right]^2. \qquad (4)$$

The K constant, derived experimentally and covering a rather large interval of Reynolds numbers, equals 0.8.

### III.3.5. Effect of a Model

Although no systematic study was undertaken into the blocking effect of a model on diffuser efficiency, certain preliminary experiments have shown that the testing of typical models (reentry bodies) of a relative size $A/A_0$ in the order of 5% lead to losses of no more than 10%.

## IV. CONCLUSIONS

A systematic experimental study of hypersonic diffusers, which have a baffle and a cylindrical mixer, has been carried out, at a low Reynolds number, for an open jet wind-tunnel. The results achieved indicate that high recovery factors (of as much as 30 to 50 times the nozzle output pressure $p_0$) can be obtained at Mach numbers in the order of 8 for a $p_0$ pressure level of 100 μ.

Analysis of diffuser operation has provided a basis for the determination of the respective roles of the two essential elements of which the diffuser is comprised:

- the intake geometry (angle and relative entrance section) has a decisive effect on the level of the box pressure, but no effect on the overall optimum efficiency of the diffuser; satisfactory adaptation of the intake, for a large range of operating conditions, may be achieved with the following characteristics: $A_r/A_0 \sim 3$, $3° < \alpha_r < 6°$;
- pressure recovery is essentially the function of the mixer; gain increases, as the mixer diameter decreases, up to a limiting value, imposed by nozzle priming conditions.

A simple theoretical prediction of diffuser performance has been proposed. It is in good agreement with actual recovery levels, provided an empirically determined correction factor is introduced.

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